

Applications of Pretensioned Anchor Rods in Industrial Facilities

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ABSTRACT

Base plate and anchor rod connections are key structural components. A great majority of anchor rods are designed, placed and installed without pretensioning, usually because the structures are considered to be statically loaded. Applications of pretensioned anchor rods are less common and generally limited to certain industrial facilities. This paper provides a brief overview of the current state of the practice regarding pretensioned anchor rods and reviews selected recent pretensioned anchor rod applications in power industry facilities.

Keywords: pretensioned anchor rods, column base connections.

INTRODUCTION

Base plate and anchor rod connections are key structural components of vital importance to the plumbness and safety of structures. They are not only used as column base support in every building structure, but also utilized for supporting nonbuilding structures and mounting of equipment in industrial facilities. Anchor rods, a relatively new terminology adopted by AISC, were referred to as anchor bolts in the past. A great majority of anchor rods are designed, placed and installed without pretensioning. Base plates are tied to anchor rods by nut(s) and washer, as evidenced in typical building column bases. Applications of pretensioned anchor rods are less common and generally limited to certain industrial facilities. Design of column base plates and anchor rods is governed by the AISC *Specification for Structural Steel Buildings* (AISC, 2005) and ACI 318 Appendix D (ACI, 2005). However, neither the AISC *Specification* nor ACI 318 provide specific guidelines for pretensioned cast-in-place anchors. An excellent guideline, AISC *Design Guide 1, Base Plate and Anchor Rod Design*, second edition, second printing (Fisher and Kloiber, 2006), is now available to guide engineers and fabricators for design, detailing, fabrication and erection of column-base-plate and anchor rod connections. Appendix 3 of the design guide provides limited but useful discussions on pretensioned anchors. It appears that similar guidelines or authoritative design codes/standards are still lacking with respect to design, fabrication and installation of pretensioned anchor rods, and little research has been done in this area. Engineers often have to rely on their own past

experience and engineering judgment to develop a satisfactory application. Information and design practices published in literature are not consistent, sometimes confusing and conflicting. This paper is written with two objectives: (1) to provide a brief review of the current state of the practice in pretensioned anchor rods; and (2) to present lessons and knowledge learned from selected recent project applications in power industry facilities.

For many years, AISC noted that the pretensioning of anchor rods was not recommended for building structures. Commentary Section A3.4 of the 1999 Edition AISC *LRFD Specification* noted concerns regarding prestressing relaxation due to concrete creep and the potential for stress corrosion damage. The author believes that the reason most building structures do not have pretensioned anchor rods is that the structures are statically loaded. The Commentary note is not present in the 2005 AISC *Specification*. In view of this historical background in the building industry, it would be very beneficial to examine the practices of pretensioning of anchor rods outside the building industry.

WHEN PRETENSIONING IS RECOMMENDED

According to *Design of Anchor Bolts in Petrochemical Facilities* (ASCE, 1997), pretensioning of anchor rods is recommended for the following three situations:

- Tall vessels sensitive to wind such as towers with a height-to-width ratio of 15 or more, or more than 100 feet tall.
- Dynamic machinery such as compressors or other pulsating equipment.
- High-strength anchor bolts to minimize load reversals.

These three pretensioning applications all aim to improve the long-term performance of anchor rods or to improve the

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performance of equipment or vessels. One common denominator among these applications is that the anchor supports are subjected to frequent load fluctuations induced by wind, thermal cycling or machine vibrations. Pretensioning helps prevent fluctuation of the tensile stress in the anchors and therefore minimizes loosening of nuts and alleviates fatigue concerns. Anchor pretensioning may also help decrease machine vibrations and the drifts of process vessels under wind or other lateral loads.

In addition, pretensioning of anchor rods will increase the frictional shear resistance at base plates, which is beneficial for the design of anchorages for tall vessels and structures subjected to heavy wind and seismic forces. Certainly, wind-sensitive structures are not limited to tall process vessels. Other examples include steel stacks, pipe rack supports, piping supports, crane column bases, transmission poles, wind turbine towers, telecommunication towers and cantilevered signal- and light-support structures for highways.

AISC *Design Guide 1* (Fisher and Kloiber, 2006) states that vibratory machine joints and double-nut joints designed for high seismic applications (Seismic Design Category D, E and F) or designed for fatigue require pretensioning according to ASCE/SEI 7 (ASCE, 2005).

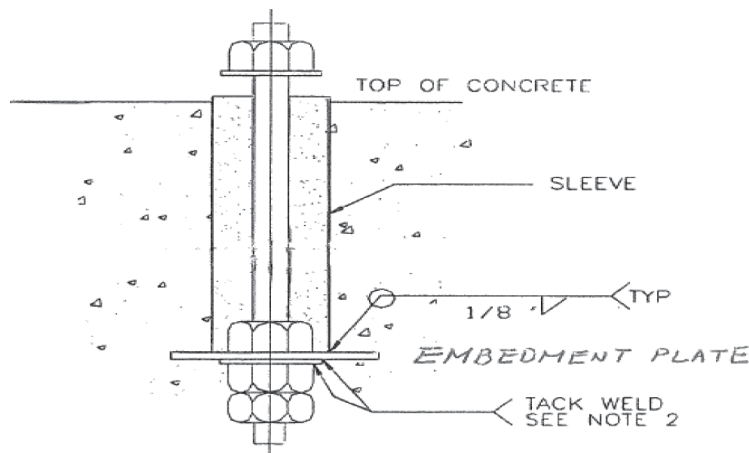
For each such application, engineers are advised to balance the previously mentioned technical advantages against the possible cost increases, which could range from little to very substantial, depending on the size of anchor rods and the pretension magnitude desired. There are a number of other potential shortcomings caused by pretensioning that should not be overlooked. One of them is the damage to concrete and grout that may result from inadequate design or excessively high pretension loads. Improper tensioning methods and/or improper tensioning sequences can cause

damage. Other shortcomings include lack of high assurance that the anchor is properly installed and pretensioned in the field. Periodic examination and testing may be needed to monitor the loss of pretension over time caused by concrete creep and anchor relaxation.

CONFIGURATIONS OF THREE TYPES OF PRETENSIONED ANCHOR ROD JOINTS

Three commonly used pretensioned anchor rod joints are shown in Figures 1a, 1b and 1c.

Figure 1a represents a typical vibratory-machine joint in which the sleeve is extended for the full depth of the anchor. The sleeve is used for both precise alignment and pre-tensioning of anchor rods. The sleeve is usually made of metal pipes. Long metal sleeves can be substituted with plastic (PVC) sleeves if no welding is required. Either single or double nuts may be located beneath the embedment plate. The space between the anchor rod and pipe sleeve can be filled with grout after the structure or equipment is set, aligned and pretensioned. Alternatively, sleeves may be sealed on top or filled with appropriate elastomeric material to prevent water or grout from filling the sleeve. It should be noted that if sleeves are not grouted, anchor rods will not be effective in resisting shear loads and will have to rely on shear friction tension or shear lugs for shear resistance. The metal sleeves are generally at least 1.0 in. larger than the anchor rod diameter. AISC *Design Guide 1* (Fisher and Kloiber, 2006) recommends that full-depth steel sleeves be used to minimize concrete creep/shrinkage. The full-depth steel sleeve permits elongation of the entire length of anchor rod and should have adequate strength for transferring anchor rod pretension from the embedment plate to the base



Notes:

1. Base plate and grout placed above concrete are not shown for clarity in Figure 1a and 1b.
2. If high strength anchor rods are used, welding of nuts to the anchor rods is typically not recommended.

Fig. 1a. Pretensioned anchor rods for vibratory equipment support.

plate. The embedment plate should also be capable of resisting the pretension force prior to placement of grout. Also, a hardened plate washer with appropriate thickness may need to be placed directly above the base plate when anchor pretension is high.

Figure 1b shows a pretensioned anchor rod design with a partial-depth sleeve. Partial-depth sleeves are primarily used for alignment purposes and are suitable only for applications where pretension is low or moderate. In order to allow pretensioning of anchor rods, grout below the sleeve must not be allowed to bond to the anchor rod. Typically, the portion of anchor rod shaft below the sleeve and within 1 in. of the embedment plate is taped or coated with a bond-breaker for a distance at least six times anchor rod diameter above the embedment plate, so that the anchor rods can be adequately stretched (ASCE, 1997). The sleeves are typically positioned with a distance at least six times anchor rod diameter above the embedment plate.

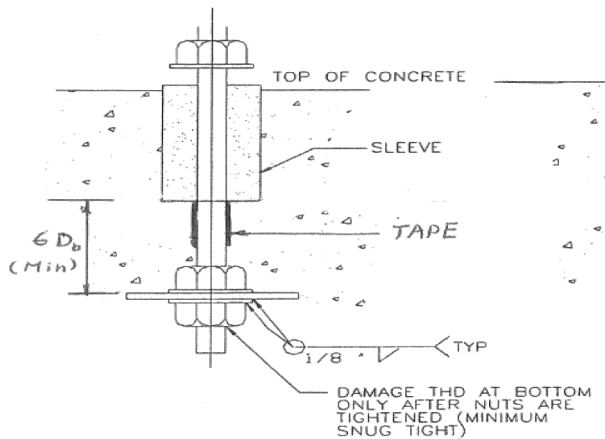


Fig. 1b. Pretensioned anchor rod with partial-depth sleeve.

Figure 1c shows configuration of a typical double-nut-moment joint at column base. The base plate is attached to anchor rods through double nuts (a leveling nut and a top nut). Washers are typically used under both nuts. The base plate stands off from the concrete foundation and bearing on leveling nuts. Grout is not typically placed beneath the base plate. Anchor rods are designed for axial loads (tension and compression), shear and moment. Double-nut-moment joints are easy to level and plumb and are also very reliable for transmitting moment to the foundation; therefore, they are satisfactory for nonredundant structures and seismic or fatigue-loaded structures. This type of column base design is commonly used in highway ancillary structures, towers and poles, which are subjected to significant moments and shears. Double-nut joints are pretensioned between nuts only. Research performed for National Cooperative Highway Research Program (NCHRP) Reports 469 and 412 (Dexter and Ricker, 2002; Kaczinski et al., 1996) shows that pretension in the rod between two nuts improves fatigue strength by good load distribution among the anchor rods.

PRETENSIONING VALUE

For any pretensioned anchor application, the first question raised by designers is how much pretension to apply. The answers to this question vary with the intended application. Table 1 gives a summary of various pretension practices in power, petrochemical process and highway industries. It can be seen from Table 1 that the pretension load desired may vary from $0.15F_y$ (15% of the specified minimum yield strength of anchor rod) to as high as $0.6F_u$ (60% of the specified minimum tensile strength of anchor rod), depending on the design objectives.

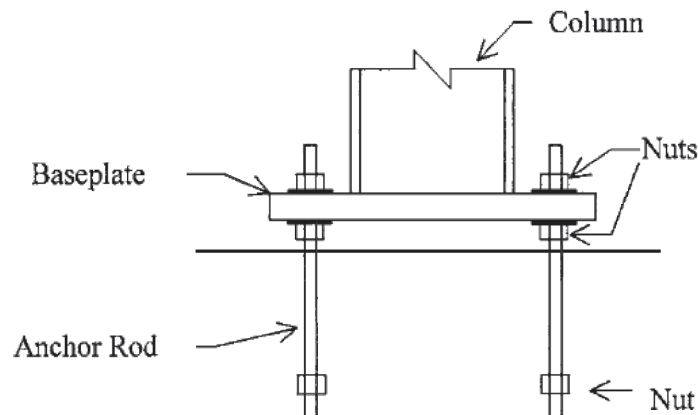


Fig. 1c. Typical double-nut-moment joint.

Table 1. Summary of Various Anchor Rod Pretensioning Practices

	Vendor 1		Vendor 2		Vendor 3	Vendor 4	Vendor 4	AISC Design Guide 1 (2006)	ACI 351-3R (2004)	ASCE Anchor Rod Design (1997)
	Turbine Support	Generator Support	Turbine Support	Generator Support	ID/PA/FD Fan	ID/PA/FD Fan	Motor	Double-Nut-Moment Joint at Column Base	Vibratory Equipment	See Note 6
Anchor Rod Diameter	2 in. to 2½ in.	1½ in. to 2 in.	2 in. to 2½ in.	1½ in.		1¾ in.	2 in.	≤ 4 in.	No limit	
Pretension Load	None	Approx. 55 kips for 2-in. anchor rod (17,500 psi or $0.5F_y$)	18,500 psi ($0.18F_y$)	30,000 psi ($0.28F_y$)	None	32,000 psi	30,000 psi	$0.5F_u$ for Gr. 36 and $0.6F_u$ for higher strength	Sufficient to resist dynamic shear loads by shear friction; $0.15F_y \leq F_t < 0.7 F_y$	$F_t = 0.3; F_u$ unless otherwise required; 17,400 psi to 18,000 psi for A36 or A307 Gr. C; 37,500 psi for Gr. 105
Installation Torque	50 ft-lb (Notes 2, 3 and 4)	1,100 ft-lb for 2-in. anchor rods and 840 ft-lb for 1½-in. anchor rods (Notes 2 and 3)	Not specified	Not specified	None	1,560 ft-lb	1,900 ft-lb	Minimum nut rotation specified	Bolt torque should be determined based on preload required	
Sleeves	Yes	Yes	Yes	Yes	Not Required	Yes	Yes	No	Yes	Yes for vibratory machine
Grouting sleeves	Yes (Note 1)	Yes (Note 1)	Yes (Note 1)	Yes (Note 1)	N/A	Yes (Note 1)	Yes (Note 1)	No	Yes (Note 1)	No for vibratory applications; fill sleeves with elastomeric materials
Minimum Grout Strength	7,000 psi at 28 days and 5,000 psi at 7 days (Note 5)	7,000 psi at 28 days and 5,000 psi at 7 days (Note 5)	7,500 psi	7,500 psi	None	None	None	Not specified	None	None
Bolting (Rod) Materials	A307 Gr. C (A36) standard; use A449 Type 1 anchor rod when anchor rod size is large	A307 Gr. C (A36) standard; use A449 Type 1 anchor rod when anchor rod size is large	A193 B7 or equivalent	A193 B7 or equivalent	No restriction	A193-B7	A193-B7	F1554 Gr. 36, 55, 105 and A615 Gr. 60	No restriction	No restriction

Notes

1. Fill sleeve completely with grout after equipment is set and aligned.
2. Tighten the nuts of anchor bolts to snug-tight where fixators are used.
3. Where anchor rods are subject to thermal movements (expansion or contraction), nuts are backed off from tightened torque to provide a 0.01-in. nominal clearance between the bottom of nut and top of the washer; a nut-locking device or double-nutting should be provided.
4. Where thermal movement is not a concern, the anchor rods are generally tightened either snug-tight or with a 50 to 60 ft-lb final installed torque.
5. Use flowable, nonshrink, cementitious grout (ASTM C1107 Gr. A).
6. See page 1 for conditions recommended for pretensioning of anchor rods.

Vibratory Equipment Support Applications

Where pretensioned anchors are used for mounting of vibratory equipment (sometimes referred as dynamic machinery) and vibration performance is the primary objective, the pretension loads are generally set in the range of $0.15 F_y$ to $0.70 F_y$. The size, material and pretension loads or pretension stresses of anchor rods are typically specified by equipment manufacturers. Pretensioning of the anchor rods enables the equipment and foundation to act as an integral structure to allow smooth transmission of machine unbalance force to the foundation. Proper pretension provides sufficient clamping force to maintain critical alignment of the machine. Others consider the pretension has a spring effect that will absorb and dampen vibration levels. Unlike high-strength bolts in steel-to-steel connections, the pretension loads in anchor rods required may be expressed either as tensile stress or installation torque. Most rotary equipment such as gas turbines, steam turbines, generators, electric motors, pumps and fans have a specified minimum pretension of $0.15 F_y$ to $0.50 F_y$. A minimum pretension load of $0.15 F_y$ is the recommended value by ACI 351.3R (ACI, 2004) for foundation anchors supporting rotating equipment. Supports for reciprocating equipment (compressors, hammers, diesel generators, etc.) generally require larger pretension loads because the machine produces large horizontal dynamic forces. The pretension loads for these vibrating equipment supports can be as high as $0.8 F_y$. For precision machines, designing for a clamping force equal to 150% of the anticipated normal operating bolt force is a common practice to account for uncertainty in bolt tensioning and creep/shrinkage. Higher clamping force is typically achieved with more anchor bolts or larger pretension force.

In establishing anchor pretension, considerations should be given to thermal friction and the use of fixators. Where anchor rods are subject to thermal movements due to expansion or contraction of equipment, some turbine manufacturers recommend that nuts to be backed off from the tightened torque to provide a 0.01-in. nominal clearance between the bottom of nuts and top of the washer. In addition, a nut locking device or double nutting is often provided to prevent loosening of the nuts.

Leveling of mounting base for heavy machinery can be challenging and time-consuming. To achieve efficient mounting, many equipment manufacturers recommend the use of sliding shims or fixators. The later is a special anchoring and leveling device that permits precise alignment adjustments to be made after anchor nuts are tight. Where fixators are employed, anchor rods are usually installed snug-tight to avoid damage.

Highway Cantilever Structure Support Applications

Anchor pretension higher than $0.5 F_y$ may be necessary to maintain the tensile stress in the rod from fluctuating during

load reversal generated by wind induced vibrations. An excellent discussion of the minimum pretension loads is given in NCHRP Report 469 (Dexter and Ricker, 2002) for anchor rods used on highway ancillary structure supports. Extensive fatigue testing has been performed on anchor rods in the early 2000s, including NCHRP Report 412 (Kaczinski et al., 1996). The research in this report shows that the threshold tensile fatigue stress range of anchor rods is 7 ksi, which is very low. As a result, fatigue evaluation is not required if the stress in anchor rod remains in compression during the entire load cycle or if the stress range from applied loads is less than the threshold tensile stress range (7 ksi). This research showed that column base plate–anchor rod connections subjected to more than 20,000 repeated application of axial tension and/or flexure stress range must be checked for fatigue. Their testing suggested that the allowable stress range of anchor rods at 20,000 cycles is approximately 27 ksi. Thus, pretensioning of anchor rods to minimize stress fluctuation can be extremely beneficial for base plate–anchor rod connections that are subjected to large number of tensile stress cycles. Because highway cantilevered support structures are subjected to many cycles of wind loads, including vortex shedding vibrations, natural wind gust, galloping and thrust gusts, NCHRP Report 469 recommends that all anchor rods in the double-nut moment base joints be pretensioned to a minimum value equal to $0.5 F_u$ (i.e., 50% of the specified minimum tensile strength) for low-strength rod, namely, ASTM F1554 Rod Grade 36, and $0.6 F_u$ for anchor rods made of higher-grade steel. These recommended minimum pretension loads are equivalent to 80% of the specified minimum tensile yield strength for Grade 36 rods, $0.818 F_y$ for Grade 55 rods, $0.714 F_y$ for Grade 105 rods, and $0.8 F_y$ for Grade 60 ASTM A615 and A706 bars.

Since the late 1970s, studies of tensile fatigue of anchor rods have been made at several major universities. A general study of anchor rod fatigue was made by Frank (1980) at the University of Texas. This research showed that for double-nut moment base plate joints, tightening the double nut connections $\frac{1}{3}$ of a turn beyond snug-tight significantly improved fatigue life. More research, including Van Dien et al. (1996), Richards (2004), and Hodge (1996) followed after the failures of cantilevered highway signs across the country, particularly in Michigan. Research further confirms the value of preloading the anchor bolts. An excellent summary of the tensile fatigue resistance of anchor rods and recommendations is given by *NCHRP Report 469* (Kaczinski et al., 1996). It states that the S-N fatigue curve for nonpretensioned anchor rods corresponds to the Fatigue Stress Category E' of Appendix 3 of the *AISC Specification* (AISC, 2005), except that the fatigue threshold is 7 ksi, which is much higher than other Category E' details. If the anchor rod in double-nut-moment and vibratory-machinery joints is properly pretensioned, the rods will have tensile fatigue

resistance as good as Category E; however, the fatigue threshold is improved little. Because tests show that the alignment eccentricity of anchor rods in the field can have adverse effects on fatigue resistance, the report recommends that Category E' be used for design regardless of the pretension. The anchor rod misalignment should be kept below 1:40. These recommendations from *NCHRP Report 469* can serve as a guide to engineers for establishing the pretension needed for a specific application.

Support of Tall Process Vessels, Process Towers, Steel Stacks and Wind Turbine Towers

For tall process vessels, process towers, steel stacks and wind turbine towers, there is no consensus on anchor rod pretension requirements. Some engineers choose to use a very high pretension in anchor rods equal to the maximum uplift forces caused by factored wind overturning moments. This conservative pretension is intended to ensure that tension in anchor rods will never exceed the initial anchor pretension force during the life of the structure. Others have chosen to use a lower pretension equal to the maximum uplift that may be produced by the design wind (nonfactored) or a fraction (50 to 70%) of the design (factored) wind moment. Past experience and research by Dexter and Ricker (2002) shows that fatigue is generally not a problem when the number of cycles that exceed the anchor pretension force is small (less than 20,000 cycles) during the life of the structure. In any case, it will be prudent to evaluate the effect of tensile fatigue on anchor rods and compression fatigue on concrete when pretension is not set to the maximum uplift force. Where operating load spectra are not available, a minimum pretension of $\frac{1}{3}F_u$ is recommended by *Design of Anchor Bolts in Petrochemical Facilities* (ASCE, 1997).

Steel stacks are another type of wind-sensitive structure. Many stacks are susceptible to cross-wind (or vortex shedding)-induced vibrations. According to the steel stack design standard ASME STS-1 (ASME, 2006), anchor bolts should be properly torqued and retightened 30 days after stack erection. However, the standard is silent on the anchor pretension requirements, and the engineer of record must determine the pretension requirements. Where stacks are properly proportioned to preclude significant vibrations, anchor rods are typically tightened by $\frac{1}{4}$ turn beyond the snug-tight condition. The $\frac{1}{4}$ turn from snug-tight has also been a standard industry practice for tightening of anchor rods for building column base connections and static equipment supports. The pretension stresses obtained by tightening nuts $\frac{1}{4}$ turn from snug-tight vary substantially, depending on the anchor yield strength, embedment length, concrete strength, pitch of threads and the lubrication condition of nuts and anchor rods.

Thus, the level of pretension of anchor rods needed for a given application is very much influenced by the expected

service environment and past industry experience. This includes any one of the following conditions:

- Ensure the anchorage is capable of withstanding significant cyclic stress fluctuations.
- Keep anchorage tight and nuts from loosening that may be caused by operation vibrations.
- Minimize the movement or drift of structures/vessels induced by foundation rotation.
- Follow the common tightening practice for a specific industry.

For applications where anchor rods and base plates are to be subjected to a large number of significant stress cycles from live loads, wind effects or other cyclic operating loads, fatigue resistance is the single most important factor for determination of anchor pretension. It is the responsibility of foundation designers to select an adequate anchor pretension load for their specific applications.

PRETENSIONING METHODS AND INSTALLATION SEQUENCE

There are three methods commonly used for applying the required preload in the anchor rods: turn-of-the-nut method, with a torque wrench and by hydraulic jacking. Among the three, hydraulic jacking is the most accurate pretensioning method and is used where the pretension load is critical to the structural integrity of the support and/or to the serviceability of the equipment. Hydraulic bolt tensioners use an annular hydraulic jack placed around the anchor rod, stretching it axially. When the required stress level is reached, the nut is tightened snugly and then the pressure released, resulting in a preloaded bolt without any frictional or torsional stresses. The hydraulic jacking method can provide very accurate preload ($\pm 1\%$) on long bolts, but it is less accurate on short bolts. The method is often used for mounting of heavy vibratory machines with large-diameter anchor rods or high-strength anchors (Grade 75, 105 or higher strength). The method is commonly used in the power industry, petrochemical industry and wind turbine industry. Calibrated hydraulic bolt pretensioners such as those manufactured by Boltech, Tantec and others have been used satisfactorily in many applications.

Torque wrench pretensioning only provides a rough measure of anchor preload. The torque wrench method is a simple and easy method for field preloading. However, torque is not a reliable indicator of bolt tension and is sensitive to lubrication and condition of bolts and nuts. The torque coefficient used in common torque-tension relationships may vary from 0.1 to 0.3. *AISC Design Guide 1* (Fisher and Kloiber, 2006) indicates that the coefficient is 0.12 for common anchor rods. Others have suggested a larger value

of 0.2 for less-well-lubricated rods. For example, the torque needed for a pretension of $\frac{1}{3}F_u$ of a 1½-in.-diameter anchor rod made of F1554 Grade 36 would be in the range of 408 to 680 ft-lb. If the rod is made of A193 B7 steel, the range will increase to 879 to 1,465 ft-lb based on the method recommended by AISC *Design Guide 1*. Despite its inaccuracy, the torque wrench method has been the method of choice for many engineers for applications where the amount of pretension needed is either not essential or not substantial. For anchor rods greater than 1 in. diameter, the torque required for anchor tightening would require the use of a slugging wrench or a hydraulic torque wrench.

Turn-of-nut method is the easiest preloading method. It gives preloads more reliable than the preceding torque wrench method. Anchor rods are first brought to the snug-tight condition, followed by turning the nut from the snug-tight condition with a predetermined number of turns. The snug-tight is generally conceived as the condition in which base plate and grout are brought into good contact by tightening nuts with a few impacts from common impact wrench. This is the method recommended by *NCHRP Report 469* (Dexter and Ricker, 2002) for tightening of the fatigue-sensitive double-nut-moment base joints. The number of nut rotations has been developed for double-nut-moment joints based on extensive testing. For other pretensioned joints, the nut rotation required beyond the snug-tight condition is not known and may have to be established by testing. It is important to note that anchor rods are typically much longer than high-strength structural bolts, varying from eight times the rod diameter to 30 ft in length. Thus, the amount of nut rotations beyond snug-tight to achieve pretension is substantially larger than high-strength structural bolts. According to *Design of Anchor Bolts in Petrochemical Facilities* (ASCE, 1997), the amount of nut rotation for the targeted pretension stress can be estimated by an approximate formula based on displacement compatibility between anchor rod and nut rotations. However, the amount of nut rotation for a given preload estimated by the formula is often found to be too low because the compression deformation of concrete and grout is ignored in the approximation. Caution must be exercised when using any approximate turn-of-nut formula.

Both torque wrench and turn-of-nut pretensioning method have been used for applications where anchor rods have a diameter of 1½-in. or smaller or where anchor rods have a shallow embedment length (less than or equal to 15 times the anchor diameter). However, for anchor rods of larger diameter or greater embedment length, pretensioning by hydraulic tensioners will be more effective.

Aside from these three methods, load indicating mechanisms, such as direct tension indicators (DTI), are getting more popular. They are often used in verifying preloads installed by torque wrench and turn-of-nut method. They serve as an alternative means to hydraulic jacking to achieve accurate pretension desired.

Multiple anchor rods are used for mounting heavy equipment, large process vessels, cantilevered poles and tower masts, and steel stacks. Anchor rods may be tightened in two or three stages. The three-stage tightening sequence is a more current trend in the industry, with 50% of full-pretension applied to all anchors in the first stage, 90% in second stage and 100% full pretension applied in the last stage. *Design of Anchor Bolts in Petrochemical Facilities* recommends that anchor rods should be tightened in criss-cross or star pattern. Similar tightening sequence is also followed in anchoring wind turbine towers.

Installation sequence for pretensioned joints is provided in Appendix A of AISC *Design Guide 1* (Fisher and Kloiber, 2006). Due to creep and stress relaxation, anchor pretension should be monitored periodically and anchors should be retightened if necessary. ACI 355.1R (ACI, 1997) reported that the final tension in headed anchors are typically in the range of 40 to 80% of the initial preload due to creep of highly stressed concrete under the anchor head. The loss of pretension depends on bearing stress under the anchor head, concrete deformation and the anchor depth. It also reported that pretensioning the anchor 90 days after the initial tightening can reduce the pretension loss by more than 50%. Anchors tightened 90 days after concrete placement then retightened 1 year later can further reduce loss in pretension (80% less). For fatigue critical applications such as wind turbine tower supports, engineers often specify that anchor rod pretension be checked once within 6 months after anchor installation and every 3 years thereafter. Loosened anchors should be retightened with hydraulic jacking. AISC *Design Guide 1* also recommends that all pretensioned anchor joints designed for Seismic Design Categories D, E or F be inspected and maintained after a significant seismic event.

Where epoxy grout is used, creep under high compression can cause a significant loss in anchor bolt pretension, which reduces the ability of the anchor bolt to maintain high frictional resistance to relative motion between vibrating equipment and tie-downs. The effects of creep must be considered in pretensioning of anchor bolts as well as in the engineering of grout thickness, anchor bolt length and preload tension as recommended by *Design of Anchor Bolts in Petrochemical Facilities* (ASCE, 1997) and *PCI Design Handbook* (PCI, 2008).

SPECIAL DESIGN CONSIDERATIONS

Designs of pretensioned anchor rods and regular anchor rods have many common aspects. Anchor rods must be capable of withstanding design loads (uplift tension loads, shear loads, compression loads and pretension force) and allowing the loads to be transferred to base plate, grout and concrete. Anchor rods should possess adequate strength to guard against bolt tensile failure and concrete pull out failure. Anchor rods located near the edge of concrete piers or foundations

should be designed for possible lateral (side) bursting failure. ACI 318 Appendix D (ACI, 2005) and AISC *Design Guide 1* (Fisher and Kloiber, 2006) provide excellent provisions/guidelines for design of nonpretensioned base plates and anchor rods.

There are, however, a few design aspects in which pretensioned anchors differ from nonpretensioned anchors and would require special consideration. These include the following:

- Pretensioned anchors should have adequate fatigue strength to resist cyclic loads (see Example 1), and bolt forces due to pry action should be included in the fatigue evaluation.
- Embedment plate, sleeve and base plate should have adequate static strength and stiffness for anchors with large pretension as discussed in *Design of Anchor Bolts in Petrochemical Facilities* (ASCE, 1997).
- Grout and concrete supporting base plates and anchors are susceptible to localized bearing damage and concrete splitting cracks when pretension force is high. A

number of recent wind turbine foundation applications required the use of 12,000-psi grout and 7,000-psi concrete.

- Friction due to anchor pretension is available for shear resistance. As a result, shear lugs are not often used in pretensioned anchors. According to *Design of Anchor Bolts in Petrochemical Facilities*, friction resistance may also be considered for seismic shear if anchor rods are pretensioned to twice the seismic uplift force, except that no more than 50% of friction resistance should be provided by pretension.

SELECTED EXAMPLES OF PRETENSIONED ANCHOR APPLICATIONS

Example 1

This example involves the design of a spread footing with a central pedestal to support a wind turbine tower as shown in Figure 2. The turbine tower is anchored to the concrete pedestal via a base ring plate and 140 high-strength anchor rods. Anchor rods are to be fabricated from No. 10 A615 Grade

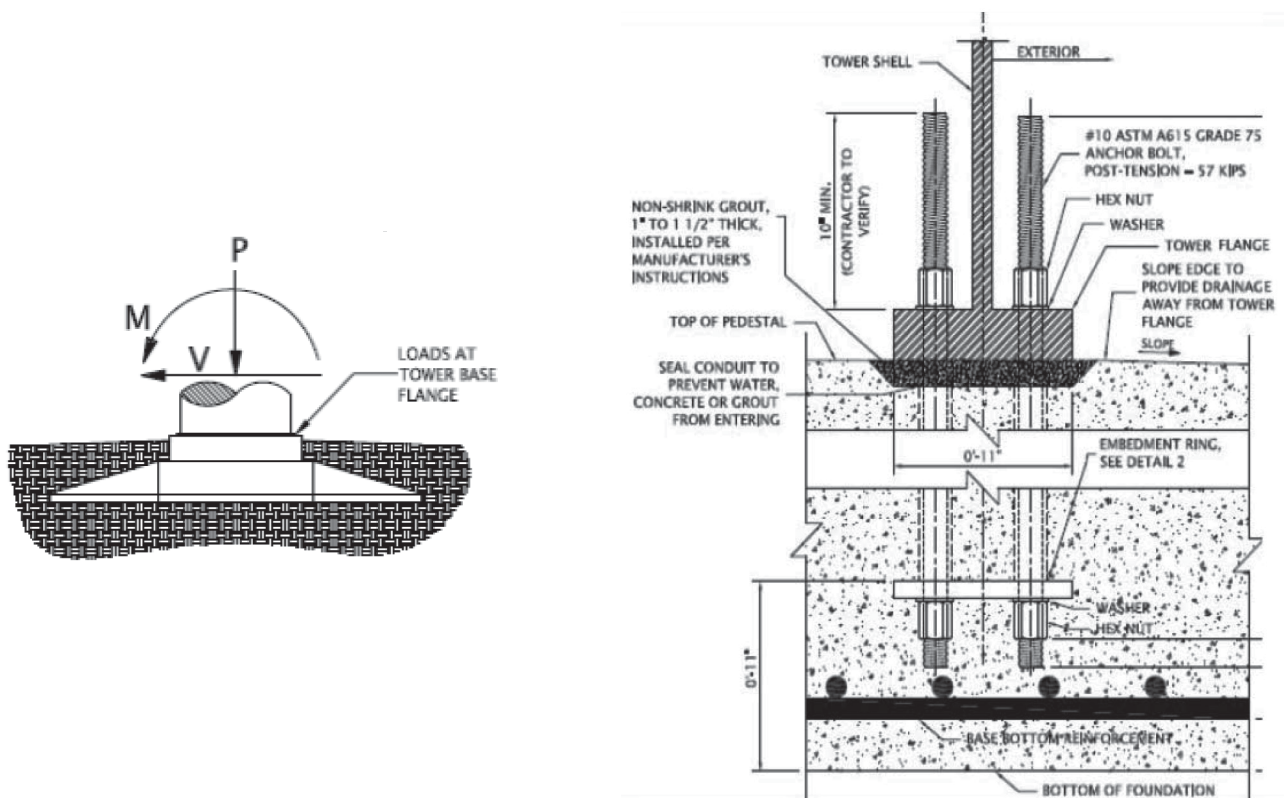


Fig. 2. Sketch of wind turbine foundation and tower anchorage to foundation for Example 1.

75 threaded bars. The anchor rods are arranged in two concentric circles with 70 anchor rods evenly spaced along each bolt circle. The diameter of the inner bolt circle is 13 ft 6 in.; the diameter of the outer bolt circle is 14 ft 6 in. The tower anchorage is designed for an unfactored wind moment, M_w , of 25,747 kip-ft, a horizontal shear load (V) of 118 kips, and a dead load, P , of 415 kips. In addition, the turbine manufacturer requires the anchorage to have adequate fatigue resistance against operating load spectra with cyclic overturning moment changes from nominal to a value as large as the design wind moment. A complete design of this wind turbine foundation will require a geotechnical evaluation, a static strength design, a structural stability analysis, a foundation dynamic stiffness analysis, and a static and fatigue strength of anchorage. However, the focus of this example is limited to the determination of anchor rod pretension only.

Note that Grade 75 threaded bars are the anchor rods most commonly used in the wind turbine industry, although their use at building column base is rare. The material has excellent strength: $F_y = 75$ ksi (minimum yield strength) and $F_u = 100$ ksi (minimum tensile strength) and excellent bond strength to concrete. Grade 75 threaded rods are available in many diameters ($\frac{3}{4}$ to $3\frac{1}{2}$ in.) and in lengths up to 50 ft. The net tensile area at the threads of a No. 10 threaded bar is 1.27 in.²

First, the maximum uplift force in anchor rods, T_b , due to unfactored design moment can be estimated by the following approximation equation given by ASME STS-1 2006:

$$T_b = \frac{4M_w}{ND_b} - \frac{P}{N} + \frac{V}{(\text{friction coefficient at grout} \times N)}$$

where

D_b = average diameter of the inner and outer bolt circles

N = number of anchor rods

$$T_b = \frac{4(25,747 \text{ kip-ft})}{(140)(14 \text{ ft})} - \frac{415 \text{ kips}}{140} + \frac{118 \text{ kips}}{(0.55)(140)} = 51.3 \text{ kips}$$

A more accurate determination can be made on the basis of moment of inertia considering exact locations of anchor rods. Maximum tension in the outer anchor rods is 57.1 kips.

There is no unique way for prescribing the pretension loads. One can set the pretension in the anchor rods equal to 57.1 kips (45% of the tensile strength of the rod) or 72.4 kips at the factored moment (57% of the tensile strength of the rod), or at a pretension of 42.0 kips (which is close to one-third of the rod tensile strength). If the pretension is set at 72.4 kips, the anchor rods will not be subjected to net uplift

forces during their service life, and tensile fatigue of anchor rods is unlikely. Conversely, the tensile fatigue resistance of anchor rods should be evaluated for the other two cases where lower anchor pretension loads are selected.

According to the turbine manufacturer for this project, the turbine tower is expected to experience a mean overturning moment of 10,873 kip-ft and a fatigue damage equivalent cyclic moment range of 30,393 kip-ft at 1,000,000 cycles using a method recommended by *Guidelines for Design of Wind Turbines* (DNV/RSO, 2002). Therefore, the anchor rods will be stressed to a tensile stress 1.3% higher than the initial pretension at the maximum cyclic moment if pretension is set at 57 kips. Thus, the anchor rods should have adequate fatigue strength. However, the anchor rods will be stressed to a maximum tensile stress 37.4% higher than the initial pretension if the anchor rod pretension load is set at 42 kips. The tensile stress range is therefore equal to $(0.374)(\frac{1}{3})(100 \text{ ksi}) = 12.5$ ksi.

Per AISC *Specification* (AISC, 2005) and ACI 351.3R-04 (ACI, 2004), the allowable stress range of the anchor rods can be determined as follows:

$$F_{sr} = \left(\frac{C_f}{N} \right)^{0.333} \geq 7 \text{ ksi} = \text{fatigue threshold}$$

where

C_f = fatigue constant = 3.90×10^8

N = 1,000,000 cycles

$$F_{sr} = \left(\frac{3.90 \times 10^8}{1,000,000} \right)^{0.333} = 7.3 \text{ ksi}$$

The tensile stress range of 12.5 ksi from the operating load spectra will exceed the above allowable stress range by 70%. Therefore, the pretension of 42.0 kips is too low and has to be adjusted to a higher value.

Note that the effective pretension in anchor rods with an initial tension of 57.1 kips will decrease to 42.8 kips if a 25% loss is considered. Hence, anchor rods with an initial pretension of 57.1 kips may not have adequate fatigue strength unless the anchor tension is periodically monitored and readjusted.

This example shows that the fatigue strength of anchor rods is sensitive to anchor pretension. A proper selection of initial pretension is critical to the long-term fatigue performance of wind sensitive structures.

Example 2

A compressor weighing 600 kips is supported on a concrete block foundation via soleplate and epoxy grout. The compressor is expected to produce a maximum dynamic

horizontal force of 200 kips. Assume the machine will require a total of eight 1¾-in.-diameter anchor bolts and the coefficient of friction at the critical interface is 0.15. This example will determine the preload tension required in the anchor bolts and the bolt material required.

To avoid slippage under dynamic loads at any interface, the friction force, F , at any interface between the compressor frame and soleplate, or soleplate and epoxy grout, or grout and foundation top surface must exceed the maximum horizontal dynamic force, H_{max} :

$$F = C_f (W_m + NT_{min}) \geq H_{max}$$

where

C_f = friction coefficient = 0.15

T_{min} = minimum preload tension

W_m = machine weight = 600 kips

H_{max} = maximum horizontal load = 200 kips

N = number of bolts = 8

$$\begin{aligned} T_{min} &= \frac{H_{max}/C_f - W_m}{N} \\ &= \frac{(200 \text{ kips}/0.15) - (600 \text{ kips})}{8} \\ &= 91.7 \text{ kips} \end{aligned}$$

Because the recommended clamping force is 150% of the required value, the minimum pretension is 137.5 kips. The bolt stress due to pretension is $137,500 \text{ lb}/1.90 \text{ in.}^2 = 72,368 \text{ psi}$, where net tensile area of anchor rod is 1.90 in.^2 . Per ACI 351.3R, the ratio of prestress to yield stress should be between 0.15 and 0.8. Thus, the minimum required yield stress of anchor bolts is $72,368 \text{ psi}/0.8 = 90,460 \text{ psi}$.

Select ASTM A193 B7 anchor bolts, which have a minimum yield strength of 105 ksi.

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